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13. ABSTRACT (Maximum 200 words)

We have achieved degeneracy in a mixture of the two lowest hyperfine states of ^{6}Li by direct evaporation in a stable CO_2 laser trap over time scales of 85 seconds. More than 10^5 atoms are confined at temperatures below 4 μK at full trap depth, where the Fermi temperature for each state is 8 μK. Since the trapped mixture is predicted to have a Feshbach resonance, this system is well suited for future studies of pairing interactions mediated by s-wave scattering. Scaling laws for evaporation in time-dependent optical-traps are derived. Improved evaporation at high magnetic fields yields degeneracy in just a few seconds, producing temperatures less than 3 μK in a sample containing 1.5×10^5 atoms.

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7. LIST MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORT PERIOD, INCLUDING JOURNAL REFERENCES:

1) Z. H. Lu, S. Bali, and J. E. Thomas, "Observation of Phase-dependent Temporal Correlations in Resonance Fluorescence," Bull. Am. Phys. Soc. **44**, 413 (1999).
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8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

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BRIEF OUTLINE OF RESEARCH FINDINGS

1 Scientific Progress and Accomplishments

In this program two major experimental goals and one important theoretical study have been accomplished in the past three years. The important experimental results include the first studies of direct evaporative cooling of fermions in an all-optical trap and the achievement of all-optical production of a degenerate Fermi gas. In addition, the first scaling-law theory of evaporation in time-dependent optical traps has been developed.

These achievements pave the way for important studies of trapped Fermi gas analogs of high temperature superconductivity in condensed matter systems. Since the density, temperature, and interaction strength are widely tunable in atomic systems, pairing interactions spanning the range from weak to resonantly enhanced will be possible. Further, trapped multi-component Fermi gases can be used to model few body interactions in nuclear matter. Such systems will provide widely variable data for comparision with new nonperturbative calculation methods recently developed for few-body scattering in nuclear and high energy physics.

1.1 Overview

This program explores fundamental interactions in multi-component Fermi gases. Since single component Fermi gases do not interact at low temperatures as a consequence of the Pauli exclusion principle, it is necessary to trap and cool more than one fermionic species in order to study interactions. In current experiments, ^{40}K and ^{6}Li are considered particularly promising for observation of superfluidity in a Fermi gase, because these atoms exhibit magnetically tunable Feshbach resonances in their scattering interactions. The predicted superfluidity is an atomic gas analog of a superconducting transition. For systems with resonant interactions, transition temperatures of up to half the Fermi temperature are predicted. This would make these atomic systems the highest temperature superconductors ever studied, in units of the Fermi temperature. However, the most interesting mixtures of these Fermi gases must be confined in an all-optical trap, because the states of interest are repelled from magnetic traps.

In the previous program, we developed the first stable all-optical trap for neutral atoms, which is based on a stable CO_2 laser [1]. Using this trap, a gas of fermionic

^{6}Li has been confined with a 1/e lifetime of 400 seconds. Building on this result, a primary goal of the current program became the development of evaporative cooling methods which could be applied directly in the stable CO_2 laser trap. This effort culminated in the first all-optical production of a degenerate Fermi gas last year.

The spectacular result of all-optical production of a degenerate Fermi gas has been highlighted in several places, including the AIP *Physics News Update* (March 13, 2002), Physics Today (May, 2002), and in the *Photonics News* section of Photonics Spectra (May, 2002). In addition, the work has been highlighted in longer article in Photonics Spectra (June, 2002).

In the following, the primary results of the current program are outlined briefly.

1.2 Scaling Laws for Evaporative cooling in Time-dependent All-Optical Traps.

In the past, the approach to preparing degenerate, optically trapped degenerate gases has been to achieve degeneracy in a magnetic trap, and then to transfer the gas to an optical trap. Subsequent state preparation is accomplished by employing radio-frequency transitions to produce the required mixture of atomic states. In this way, states which cannot be confined in a magnetic trap are produced in a state-independent all-optical trap. At present, no group has been able to prepare a system suitable for study of Fermi superfluidity by this method. A key problem is heating that arises during the transfer from the magnetic trap to the optical trap. In addition, imperfections in state preparation can lead to inelastic decay of some atoms and subsequent heating. This cumbersome procedure can be greatly simplified by directly producing the required degenerate mixtures by evaporation in an optical trap. Further, the all-optical method enables trapping and cooling of systems such as diamagnetic molecules which cannot be magnetically confined.

We developed the first scaling law theory of evaporation in all-optical traps which are adiabatically lowered during the evaporation sequence. Unlike the scaling laws developed previously for evaporation in constant depth magnetic traps, we include the loss of energy arising both from evaporation and from energy transfer to the trapping potential. The latter assures that the phase space density remains constant when the trap is lowered without evaporation. The predictions show that evaporation in all-optical traps can be very efficient, leading to degeneracy with relatively little atom loss.

For atomic systems with a moderately high collision rate and a high initial phase

space density, the scaling laws predict that degeneracy should be readily attainable by lowering the trap depth by a factor of about 100. These predictions were made as part of Ken O'Hara's thesis a year prior to the demonstration of a BEC in an all-optical trap by the Georgia Tech group, who used evaporative cooling in a trap lowered by about a factor of 100. Our predictions are consistent with the results of the Georgia Tech group. A Rapid Communication describing the scaling law model was published last year by our group [2].

1.3 All-Optical Production of a Degenerate Fermi Gas.

Last year, we succeeded in preparing a degenerate two-component mixture of ^{6}Li fermions by direct evaporation in a stable CO_2 laser trap [3]. We trap the two lowest hyperfine states which are predicted to have a magnetically tunable Feshbach resonance in the scattering length. The trapped mixture has the property that the scattering length is zero at zero magnetic field, enabling interactions to be turned on and off at will. This system is ideally suited for study of recently predicted resonance superfluidity and for study of the transition from weak BCS pairing to Bose condensation of strongly bound pairs.

In the experiments, we are able to trap up to 3.5×10^6 atoms in the CO_2 laser trap by loading from a ^{6}Li magneto-optical trap. Free evaporation is initiated by applying a 100 G bias field. After 6 seconds of evaporation at fixed trap depth, we obtain 1.3×10^6 atoms at a temperature of 50 μK and an initial phase space density of 8×10^{-3} per state which is very high. Forced evaporation is accomplished by lowering the trap laser intensity over 50 seconds. Using time-of-flight imaging, we find the temperature drops to 15 μK after 10 seconds of evaporation yielding $T/T_F = 1$, where T_F is the Fermi temperature. After 40 seconds of forced evaporation, $T/T_F < 0.5$ with 10^5 atoms remaining.

1.4 Scattering Interactions at High Magnetic Fields

Recently, we installed a new high-field magnet system, which produces a uniform field of up to 1100 G in the trap region. Using this system, we are exploring elastic scattering and loss in our two-state Fermi gas. In the field region near 650 G, there is loss on a time scale of a second at temperatures of 5 μK and densities of $3 \times 10^{13}/\text{cm}^3$. However, at fields just above the predicted Feshbach resonance at 850 G, there is negligible loss and heating. This bodes well for experiments on superfluidity.

We have been able to evaporate at a field of 900 G, achieving degeneracy in just a few seconds as a result of the very large elastic scattering cross section at this field. We achieve temperatures less than 3 μK in a 50-50 mixture of the two lowest hyperfine states, where the Fermi temperature is more than 9 μK. These experiments appear close to producing the requirements for observing superfluidity in a Fermi gas.

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[1] K. M. O'Hara, S. R. Granade, M. E. Gehm, T. A. Savard, S. Bali, C. Freed, and J. E. Thomas, "Ultrastable CO_2 Laser Trapping of Lithium Fermions," Phys. Rev. Lett. **82**, 4204 (1999).

[2] K. M. O'Hara, M. E. Gehm, S. R. Granade, and J. E. Thomas, "Scaling laws for evaporative cooling in time-dependent optical traps," Phys. Rev. A **64**, 051403(R) (2001).

[3] S. R. Granade, M. E. Gehm, K. M. O'Hara, and J. E. Thomas, "All-optical production of a degenerate Fermi gas," Phys. Rev. Lett. **88**, 120405 (2002).

2 Invited Talks and Seminars

During this period, our group presented 9 invited talks and seminars discussing this research:

1) "Quest for superfluidity in an optically trapped Fermi gas," Seminar on Modern Optics and Spectroscopy, M. I. T., (Cambridge, MA September 19, 2000).
2) J. E. Thomas, "Optically trapped Fermi gas," Institute for Theoretical Atomic and Molecular Physics and Physics Department, Harvard University (Cambridge, MA September 20, 2000).
3) J. E. Thomas, "Optical Trapping of a Two-Component Fermi Gas," Optical Physics Interdisciplinary Laboratories Seminar, (U. Michigan, April 3, 2001).
4) J. E. Thomas, S. R. Granade, M. E. Gehm, M.-S. Chang, and K. M. O'Hara, "Optical Trapping of a Two-Component Fermi Gas," Fifteenth International Conference on Laser Spectroscopy (Snowbird, Utah, June 10-16, 2001), invited talk.
5) K. M. O'Hara, M. E. Gehm, S. R. Granade, M.-S. Chang, and J. E. Thomas,

"Coherence in an optically trapped Fermi Gas," Eighth Rochester Conference on Coherence and Quantum Optics (Rochester, NY, June 13-16 2001), invited talk.
6) K. M. O'Hara, M. E. Gehm, S. R. Granade, and J. E. Thomas, "Two-component Fermi gas in an optical trap," 17th Interdisciplinary Laser Science Conference, (Longbeach, CA October 14-18 2001), invited talk.
7) J. E. Thomas, "Evaporative cooling of a two-component ^{6}Li Fermi gas in a stable CO_2 laser trap," Joint Workshop hosted by the Institute for Theoretical Atomic and Molecular Physics and the Harvard-MIT Center for Ultracold Atoms: *Beyond BEC: Ultracold atoms beyond mean-field physics*, (Harvard-Smithsonian Center for Astrophysics, November 2-3, 2001), invited panelist.
8) J. E. Thomas, "The quest for superfluidity in a trapped Fermi gas," (Argonne National Laboratory, November 5, 2001).
9) J. E. Thomas, "The quest for Fermi superfluidity: Implications of an all-optical degenerate Fermi gas," DAMOP 2002 (Williamsburg, May 2002), invited talk.

3 Technological Applications

Our current experiments explore the dynamics of an ultracold, trapped fermionic vapor of ^{6}Li. Potentially, these studies will enable investigation of superfluid pairing in a two-component vapor with tunable interactions. ^{6}Li has recently been shown to be the highest temperature superconductor known, when the transition temperature is measured in units of the Fermi temperature. Hence, studies in this system are likely to lead to new and fundamental insights into the nature of high temperature superconductivity which strongly impacts materials science. Further, the ultrastable CO_2 laser enables trapping of both atoms and molecules with broad applications to precision measurements and novel clocks. For example, new clocks can be based on coherent superposition states of fermions which are prevented from colliding by the exclusion principle. Our experiments are also well suited for exploring novel matter-wave-optical processes, such as abrupt transitions between interacting and noninteracting states on a time scale short compared to the time over which an atom travels a deBroglie wavelength. In this case, novel many body quantum dynamics is expected. Such experiments will enable unique studies of nonlinear atom-wave processes, enabling new techniques for manipulation and control of matter-wave fields with potential applications in nanolithography.

4 Selected Reprints/Preprints

The following reprints/preprints are included with this report:

1) S. R. Granade, M. E. Gehm, K. M. O'Hara, and J. E. Thomas, "All-optical production of a degenerate Fermi gas," Phys. Rev. Lett. **88**, 120405 (2002).

2) K. M. O'Hara, M. E. Gehm, S. R. Granade, and J. E. Thomas, "Scaling laws for evaporative cooling in time-dependent optical traps," Phys. Rev. A **64**, 051403(R) (2001).

All-Optical Production of a Degenerate Fermi Gas

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We achieve degeneracy in a mixture of the two lowest hyperfine states of ^{6}Li by direct evaporation in a CO_2 laser trap, yielding the first all optically produced degenerate Fermi gas. More than 10^5 atoms are confined at temperatures below 4 μK at full trap depth, where the Fermi temperature for each state is 8 μK. This degenerate two-component mixture is ideal for exploring mechanisms of superconductivity ranging from Cooper pairing to Bose-Einstein condensation of strongly bound pairs.

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Degenerate two-component Fermi gases offer tantalizing possibilities for precision studies of pairing interactions in systems for which the density, temperature, and interaction strength are widely variable. Of particular interest are certain two-component mixtures of ^{40}K and ^{6}Li which exhibit magnetically tunable Feshbach resonances, enabling variation of the s-wave scattering interaction from strongly repulsive to strongly attractive. Attractive mixtures in these systems are analogs of superconductors, since they have been predicted to undergo a superfluid transition as a result of Cooper pairing at experimentally accessible temperatures [1,2]. Recently, two groups have predicted the possibility of superfluidity arising from strong pairing in the vicinity of the Feshbach resonance [3,4]. Transition temperatures of up to half the Fermi temperature are predicted to result from the strong coupling of the two-state Fermi gas to the bosonic molecular state which causes the resonance. Since most high temperature superconductors achieve transition temperatures of only a few percent of the Fermi temperature, two-state Fermi gases may be the highest temperature Fermi superfluids ever studied [5]. Further, these systems may permit observation of the transition from weak Bardeen-Cooper-Schrieffer superfluidity to Bose condensation of strongly bound pairs [6].

In contrast to Bose-Einstein condensates, which can be prepared and studied in magnetic traps, two-component Fermi superfluids must be prepared in state-independent optical dipole traps, since the required pairs of hyperfine states in ^{6}Li and ^{40}K are high-field seeking [1,2,7]. A degenerate Fermi gas has been produced by direct evaporation of a two-state mixture of ^{40}K in a magnetic trap, using a dual radio-frequency–knife method [8]. Sympathetic cooling of fermionic ^{6}Li to degeneracy also has been achieved by using mixtures of ^{6}Li with bosonic ^{7}Li in a magnetic trap [9,10]. However, to explore superfluidity in these systems, transfer to an optical trap and subsequent state preparation is required. The procedure for preparing an optically trapped two-state Fermi gas can be greatly simplified by direct evaporation in an optical trap.

In this Letter, we demonstrate all-optical production of a degenerate mixture of the two lowest hyperfine states of fermionic ^{6}Li in a stable, CO_2 laser trap [11]. The trap is loaded from a magneto-optical trap (MOT) at an initial temperature of 150 μK. Degeneracy is obtained by forced evaporation, accomplished by continuously lowering the trap depth; the trap is then adiabatically recompressed to full depth. At this stage, more than 10^5 atoms remain at temperatures below 4 μK, less than half of the Fermi temperature of 8 μK. These results are consistent with scaling laws we have derived for the phase-space density as a function of trap depth [12].

Our ^{6}Li experiments employ a CO_2 laser trap with a single focused beam, rather than a crossed-beam geometry as used recently to produce a ^{87}Rb Bose-Einstein condenstate (BEC) by forced evaporation [13]. Nevertheless, after free evaporation at full trap depth, we achieve a very high initial phase-space density of $\simeq 8 \times 10^{-3}$, somewhat larger than that obtained after free evaporation in the ^{87}Rb BEC experiments.

A commercial, radio-frequency–excited CO_2 laser (Coherent-DEOS LC100-NV) provides 140 W at $\lambda = 10.6$ μm for the trapping laser beam. An Agilent (6573A) power supply produces stable current for the radio-frequency source, yielding a very stable laser intensity. The laser output is deflected by an acousto-optic (A/O) modulator to control the power. A cylindrical ZnSe telescope corrects the output of the A/O for ellipticity, and the beam is expanded by a factor of 10 before passing through an aspherical 19.5 cm focal length lens. This lens focuses the beam into the vacuum system, yielding a $1/e^2$ intensity radius of 47 μm. The corresponding Rayleigh length is $z_0 = 660$ μm. With an incident power of 65 W in the trap region, the trap depth is estimated to be 690 μK. The corresponding radial (axial) oscillation frequency for ^{6}Li is predicted to be 6.6 kHz (340 Hz), with a geometric mean of $\nu = (\nu_x \nu_y \nu_z)^{1/3} = 2400$ Hz.

The radial oscillation frequency is measured by modulating the frequency of the A/O to produce a sinusoidal displacement at the trap focus with an amplitude of 0.2 μm. After the sample is initially prepared at a temperature of $\simeq 15$ μK, the modulation is applied for 1 s. The number of remaining atoms is measured by resonance fluorescence. Repeating this procedure as a function of modulation frequency reveals a resonance in the trap loss at 6.5 kHz, in close agreement with predictions. Parametric resonance methods [14] yield results consistent with the expected

radial and axial oscillation frequencies after correction for the expected resonance frequency shift [15].

Extremely low residual heating rates are attained in the experiments. At the maximum trap intensity of 1.9 MW/cm^2, the optical scattering rate is 2 photons per hour as a consequence of the 10.6 μm wavelength [16], yielding a recoil heating rate of only 16 pK/sec. At the background pressure of $<10^{-11}$ Torr, heating arising from diffractive background gas collisions [17,18] is <5 nK/sec. For the trap radial oscillation frequency of 6.6 kHz, the intensity noise heating time constant is estimated to be $>2.3 \times 10^4$ sec based on the measured laser intensity noise power spectrum [11]. A residual heating rate <5 nK/sec is measured at full trap depth over 200 sec. Trap $1/e$ lifetimes of 400 sec are observed.

The CO_2 laser trap is continuously loaded from a ^{6}Li MOT. The MOT is loaded from a Zeeman slower for 5 sec, after which the MOT laser beams are tuned $\simeq$6 MHz below resonance and lowered in intensity to $0.1I_{\rm sat} = 0.25$ mW/cm^2 to obtain a Doppler-limited temperature of $\simeq 150$ μK at a density of 10^{11}/cm^3. Following this loading stage, the MOT gradient magnets are extinguished and the upper $F = 3/2$ hyperfine state is emptied to produce a 50–50 mixture of atoms in the lower $|F = 1/2, M = \pm 1/2\rangle$ states [7].

The $|F = 1/2, M = \pm 1/2\rangle$ mixture is of particular interest, as it is predicted to exhibit a Feshbach resonance near 850 G [19]. A convenient feature of this mixture is that the s-wave scattering length vanishes in the absence of a bias magnetic field [19]. However, the scattering length varies between 0 and $-300a_0$ as the bias magnetic field is tuned between 0 and 300 G [19]. Hence, rapid evaporation can be turned on and off simply by applying or not applying a bias magnetic field.

The number of trapped atoms is enhanced by increasing the intensity of the CO_2 laser during the loading stage [20]. To accomplish this, the beam which emerges from the trap is recollimated after a ZnSe exit window by a 19.5 cm focal length ZnSe lens, and then retroreflected and orthogonally polarized using a rooftop mirror oriented at 45° to the incoming polarization. The resulting backward-propagating beam is refocused into the trap region through the exit lens. After passing through the trap region, this beam is diverted by a thin film polarizer to a beam dump to avoid feedback into the laser. Typically 1.5×10^6 atoms are confined in the forward propagating trap beam alone. The backward-propagating beam increases this number to 3.5×10^6.

After the CO_2 laser trap is loaded, the atoms are precooled by free evaporation. To initiate evaporative cooling, we apply a bias magnetic field of 130 G by reversing the current in one of the MOT gradient coils, yielding a scattering length of $\simeq -100a_0$. During free evaporation, a pneumatically controlled mirror slowly blocks the backward-propagating beam by diverting the power into a 100 W power meter. Since this beam is refocused, the trap region is Fourier-transform related to the plane of the blocking mirror, and the trap smoothly evolves into a single beam configuration. After 6 sec of free evaporation, the single beam trap contains $N = 1.3 \times 10^6$ atoms at a temperature $T = 50$ μK. This precooling procedure provides excellent initial conditions for the forced evaporation experiments, since the resulting phase-space density for each state at full trap depth, $\rho_i = (N/2)(h\nu)^3/(k_BT)^3$, is 8×10^{-3}, which is extremely high.

In all of our experiments, we characterize the velocity distribution of the trapped gas by time-of-flight imaging. We use the A/O modulator to turn off the CO_2 laser trap abruptly ($\Delta t < 1$ μs), permitting the gas to expand for a time between 400 μs and 1.2 ms in zero bias magnetic field. Residual A/O leakage is reduced to less than 2×10^{-5} of the maximum intensity by extinguishing the radio-frequency synthesizer output prior to the amplifier. Then a linearly polarized probe laser pulse with a resonant intensity of $0.1I_{\rm sat}$ and a detuning of 3 half linewidths ($\simeq$9 MHz) illuminates the gas for 10 μs. Simultaneously, a noncopropagating repumper, resonant with the D2 lines starting from the $F = 3/2$ state, suppresses optical pumping into the upper $F = 3/2$ hyperfine state. The probe detuning reduces sensitivity to the unresolved excited state hyperfine structure and light shifts from the resonant repumper. For the selected 9 MHz detuning, the expansion time is chosen so that the imaged cloud has a small optical absorption <35%. An achromat at the vacuum system exit window produces a 1:1 image of the atomic distribution in an intermediate plane. This plane is imaged onto a CCD camera (Andor) using a microscope objective to produce a net magnification of $\simeq$4. The magnification is calibrated by moving the axial position of the trap focus through ± 1.25 mm using a micrometer-controlled translation stage. Fitting the central peak of the distribution to a straight line yields a magnification of 3.9.

The images are processed to obtain the transverse spatial distribution by integrating the measured optical depth in the axial direction. In typical measurements, the cloud expands ballistically by 100–200 μm in 400 μs, much larger than its initial transverse dimension. In the classical regime, we assume ballistic expansion with a Maxwellian distribution. In this case, the temperature is readily determined from the transverse $1/e$ width of the cloud: $a(t) = v\sqrt{1/(2\pi\nu_r)^2 + t^2}$, where $v = \sqrt{2k_BT/M}$ is the thermal velocity and t is the time. Since $\nu_r = 6.6$ kHz, for $t \gg 24$ μs, $a(t) = vt$. Measurements of the cloud radius for several expansion times between 100 and 600 μs fit very well to a straight line.

The number of atoms is determined from the spatially integrated optical depth of the absorption image and the absorption cross section σ. For each of the $M = \pm 1/2$ magnetic sublevels of the populated $F = 1/2$ state, σ is taken to be $(\lambda^2/\pi)/[1 + (2\Delta/\gamma)^2]$, 2/3 of that of the cycling transition. Since the excited hyperfine states are unresolved compared to the linewidth $\gamma = 5.9$ MHz, this cross section contains contributions from both allowed transitions. Results for the number are consistent within

10% for several detunings Δ between 9 to 30 MHz and -30 to -9 MHz, and for variation of the camera focal plane over ± 1 mm from the plane which gives the sharpest image.

After precooling by free evaporation, further cooling is accomplished by lowering the trap depth, producing forced evaporation. We have developed scaling laws for the number of atoms, collision rate, and phase-space density as a function of trap depth U for an optical trap which is continuously lowered [12]. These scaling laws are valid for a fixed $\eta = U/(k_B T) \gg 1$. For $\eta = 10$, we find that the ratio of the final to initial phase-space density increases according to $\rho/\rho_i = (U_i/U)^{1.3}$. This result shows that lowering the trap depth by a factor of 100 should increase the phase-space density by a factor of 400, producing a degenerate sample for $\rho_i > 2.5 \times 10^{-3}$. To maintain a constant value of η, the trap should be lowered from its initial depth U_i according to the formula

$$U(t) = U_i/(1 + t/\tau)^{\beta}, \qquad (1)$$

which assures us that the lowering rate slows as the collision rate decreases [12]. Taking $\eta = 10$, we have $\beta = 1.45$ and $1/\tau = 2.0 \times 10^{-3}\gamma_i$, where γ_i is the initial elastic collision rate. For a 50–50 mixture of fermions, $\gamma_i = \pi N_i M \sigma \nu_i^3/(k_B T_i)$ with N_i the initial total number of atoms. Note that γ_i is reduced by a net factor of 4 compared to a single-component Bose gas with the same parameters. For a scattering length of $a \simeq -100 a_0$, the elastic cross section is $\sigma = 8\pi a^2 = 0.7 \times 10^{-11}$ cm^2. Using $\nu_i = (\nu_x \nu_y \nu_z)^{1/3} = 2.4$ kHz, $N_i = 1.0 \times 10^6$, and $T_i = 50$ μK, we obtain $\gamma_i = 4.4 \times 10^2$ s^{-1} and $\tau = 1.1$ sec.

Unfortunately, the A/O modulator that controls the CO_2 laser intensity produces an ellipticity which varies as the radio-frequency (rf) power is varied. The ellipticity is corrected at maximum rf power by a cylindrical telescope. However, the telescope provides only fixed compensation. Hence, as the rf power is decreased to lower the trap depth, the beam becomes elliptical, reducing $\nu_x \nu_y \nu_z$ by a factor of 2 compared to that expected on the basis of the laser power alone. Further, we find that the direction of the beam changes by 3 mrad as the rf power is reduced by a factor of 100, causing vignetting. We align the trap beam to minimize this vignetting, but beam distortion still occurs. For this reason, we cannot accurately compare our evaporation results to the scaling law model. To compensate for the loss of confinement arising from the beam distortion as the trap is lowered, we increase τ to 3 sec. The trap laser intensity is lowered using an Agilent (33120A) arbitrary waveform generator, the output of which is filtered with a time constant of 0.2 sec before being applied to the multiplier input of the A/O radio-frequency generator.

We have measured atomic velocity distributions after forced evaporative cooling for a variable time t_f. To provide a calibrated reference trap, time-of-flight images are recorded after adiabatic recompression to full trap depth over 11 sec. This also increases the spatial density and hence the Fermi temperature, while preserving the phase-space density. Figure 1 shows the velocity distribution for $t_f = 10$ sec. The total number of atoms remaining is $N = 8 \times 10^5$, corresponding to a Fermi temperature of $T_F = h\nu(6N/2)^{1/3}/k_B = 15$ μK for each state. Assuming a Maxwellian distribution, the gas is at a temperature of 15 μK, yielding $T/T_F = 1$. At this temperature, a substantial number of atoms have velocities greater than the Fermi velocity of 20 cm/sec.

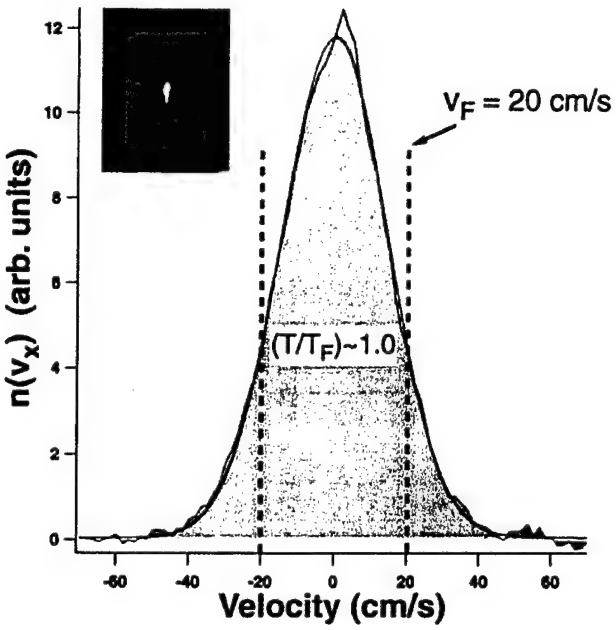

FIG. 1. Absorption image (inset) and velocity distribution after 10 sec of forced evaporative cooling followed by recompression to full trap depth. An average of five trials is shown. $T/T_F = 1$, as determined by a fit to a Maxwellian distribution. $v_F = 20$ cm/s is the Fermi velocity for a total $N = 8 \times 10^5$ atoms.

Near degeneracy, the energy of the atoms contains a contribution from the Fermi energy so that the true temperature is lower than that obtained using a Maxwell-Boltzmann (MB) distribution which assumes that all of the energy is thermal. Hence, the low temperature absorption images are fit using a Thomas-Fermi (TF) approximation to determine T/T_F [21,22], where the Fermi temperature T_F is calculated using the measured trap frequencies and integrated atom number. At the lowest temperatures achieved in the experiments, the MB temperature is $\simeq$10% higher than the TF approximation.

Degeneracy is attained for $t_f = 40$ sec, where $T \simeq 5.8$ μK and $T/T_F = 0.55$ with 3×10^5 atoms remaining. At this temperature, the gas is degenerate, and $\rho \simeq (T_F/T)^3/6 \simeq 1$ [21]. We have also measured the temperature of the atoms in the lowered trap without recompression to full trap depth. We obtain temperatures a factor of $\simeq$10 lower, i.e., $\simeq$580 nK, as expected for a harmonic trap which is lower in depth by a factor of $\simeq$100.

Figure 2 shows the velocity distribution for $t_f =$ 60 sec. The total number of atoms is reduced to 10^5,

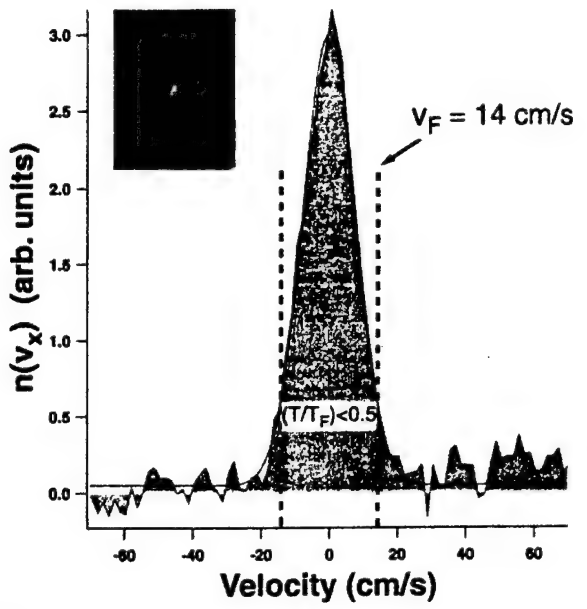

FIG. 2. Absorption image (inset) and velocity distribution after 60 sec of forced evaporative cooling followed by recompression to full trap depth. An average of five trials is shown. $T/T_F < 0.5$ as determined by a fit using a Thomas-Fermi approximation. $v_F = 14$ cm/s is the Fermi velocity for a total $N = 10^5$ atoms.

corresponding to a Fermi temperature of 8 μK. The measured temperature is below 4 μK, yielding $T/T_F = 0.48$. Nearly all atoms have velocities less than the Fermi velocity of 14 cm/sec.

In the experiments, we achieve high evaporation efficiency $\chi \equiv \ln(\rho_f/\rho_i)/\ln(N_i/N_f)$ [23]. For example, after precooling, but prior to forced evaporation, $N_i = 1.3 \times 10^6$ and $\rho_i = 8 \times 10^{-3}$ per state. After 40 sec of forced evaporation, $N_f = 0.3 \times 10^6$ and $\rho_f \simeq 1$. Hence, $\chi \simeq 3.3$. The overall evaporation efficiency is similar. Starting with the loading conditions where the total number of atoms is $N_i = 3.5 \times 10^6$ at a temperature of 150 μK, we obtain $\chi = 2.9$ after 40 sec of forced evaporation. Despite the trap distortion described above, these results are comparable to the best achieved in magnetic traps [23].

In conclusion, we have produced a degenerate, two-component ^{6}Li Fermi gas in a single beam all-optical trap by direct evaporative cooling. By using a stable CO_2 laser trap at a background pressure of $<10^{-11}$ Torr, efficient evaporation over time scales of 85 sec is achieved. In future experiments, it will be possible to attain scattering lengths of $\simeq -300a_0$ by increasing the bias magnetic field to 300 G, thereby increasing the elastic cross section at low temperature by nearly a factor of 10. This should enable preparation of a degenerate sample in just a few seconds, producing substantially lower temperatures by reducing the detrimental effects of any residual heating. We are currently preparing for a systematic study of the Feshbach resonance at higher magnetic field, and hope to observe superfluid pairing in a two-state Fermi gas.

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Scaling laws for evaporative cooling in time-dependent optical traps

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We derive scaling laws for the number of atoms, collision rate, and phase-space density as a function of trap depth for evaporative cooling in an adiabadically lowered optical trap. The results are in excellent agreement with a Boltzmann equation model and show that very large increases in phase-space density can be obtained without excessive slowing of the evaporation rate. Predictions are in reasonable agreement with a recent experiment that achieves Bose-Einstein condensation by evaporation in an optical trap. We also discuss evaporation of fermionic mixtures and explain why Pauli blocking does not strongly inhibit cooling.

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Far-off-resonance optical dipole traps are well known to provide nearly state-independent confining potentials for neutral atoms [1]. This enables study of systems that cannot be stored in magnetic traps, such as stable states of cesium atoms or diamagnetic atoms and molecules. Shallow optical traps have been used to confine multiple spin-state spinor Bose condensates [2]. Optical traps also are likely to play an important role in studies of cold neutral fermions, where specific pairs of states are required to achieve superfluidity [3–5]. A degenerate Fermi gas has been produced by direct evaporation of a two-state mixture of ^{40}K in a magnetic trap, using a dual radio-frequency-knife method [6]. Sympathetic cooling of fermionic ^{6}Li to degeneracy also has been achieved by using mixtures of ^{6}Li with bosonic ^{7}Li in a magnetic trap [7,8]. However, for both ^{6}Li and ^{40}K, exploration of superfluidity will require an optical trap. Generally, the procedure for producing an optically trapped degenerate gas has been to obtain a degenerate gas by optical cooling and evaporation in a magnetic trap, followed by transfer to an optical trap. However, direct production of a degenerate gas in an optical trap would greatly simplify many experiments, and has been explored for many years without success [9,10].

Recently, a Bose-Einstein condensate (BEC) has been produced by Barrett *et al.*, using forced evaporation of ^{87}Rb in a CO_2 laser trap that is continuously lowered [11]. In those experiments, an extremely high initial spatial density is obtained, producing a very large elastic-scattering rate as well as a high initial phase-space density. Hence, the trap depth can be lowered rapidly, producing a BEC in a few seconds.

In this paper, we describe a scaling law model of forced evaporation in a continuously lowered optical trap. The scaling law follows from a simple energy evolution equation for the trapped atoms, which includes the energy loss arising both from evaporation and from adiabatic lowering of the trap potential. Previous derivations of scaling laws for evaporation in magnetic traps have not explicitly included the time-dependent potential [12]. This is appropriate for evaporation in traps with a constant potential where the radio-frequency-knife method is employed to lower the trap threshold. Since the trap strength does not change, the explicit time-dependence of the potential has little effect, as shown by modeling evaporation from a magnetic trap with a time-dependent evaporation threshold [13]. To determine the correct scaling laws for adiabatically lowered optical traps, where the trap strength varies in time, we explicitly include the time-dependent potential and derive scaling laws for the phase-space density, number, and elastic collision rate as a function of the well depth. Results are obtained for a fixed large ratio η of trap depth U to thermal energy kT, to lowest order in the small parameter $\exp(-\eta)$, using a harmonic oscillator approximation. For $\eta = U/kT = 10$, which is typical for evaporation in optical traps, the scaling laws show that by lowering the well depth by a factor of 100, the phase-space density can be increased by a factor of 400. The corresponding elastic collision rate is reduced by a factor of 24. By including the effects of loss arising from background gas collisions, we obtain reasonable agreement with the results of Barrett *et al.* [11].

It is well known that the evaporation rate of a gas from an optical trap of fixed depth stagnates as the temperature drops [14]. At low temperatures, the number of colliding pairs of atoms with enough energy for one to leave the trap is determined by the tail of the Boltzmann distribution. Hence, the evaporation rate is suppressed by a factor $\exp(-U/kT)$. For $U/kT > 10$, the evaporation slows dramatically, and it is necessary to force evaporation by adiabatically lowering the trap depth [15].

The optical trapping potential can be written generally as

$$U(\mathbf{x},t) = -U(t)g(\mathbf{x}), \tag{1}$$

where $g(\mathbf{x})$ describes the trap shape and $g(|\mathbf{x}|\to\infty)\to 0$ with $g(0)=1$. We assume that evaporation is carried out at low temperatures near stagnation, where the average thermal energy $kT \ll U$.

To determine how the number of trapped atoms N, collision rate γ, and phase-space density ρ scale as the trap depth U is lowered, we first estimate the rate of energy loss from the trap, neglecting atom loss arising from background gas collisions. Taking the zero of energy to be at the bottom of the trap, evaporating atoms will have an average energy $U + \alpha kT$, where $0 \leq \alpha \leq 1$ [14]. From the s-wave Boltzmann equation with $kT \ll U$, we find $\alpha = (\eta - 5)/(\eta - 4)$ for any potential that is harmonic near the minimum [16]. The energy-loss rate arising from evaporation is then $\dot{N}(U + \alpha kT)$, where $\dot{N}$ is the rate at which atoms evaporate from the trap. In addition, as the trap depth is lowered adiabati-

cally at a rate $\dot{U}$, an energy change arises from the change in potential energy. Since $kT \ll U$, the atoms vibrate near the trap bottom in an approximately harmonic potential, where $E/2$ is the average potential energy. The potential energy then changes at a rate $(\dot{U}/U)E/2$ and the total energy E obeys the approximate evolution equation

$$\dot{E} = \dot{N}(U + \alpha kT) + \frac{\dot{U}}{U}\frac{E}{2}. \tag{2}$$

In the classical limit, $E = 3NkT$ is the total energy of the trapped gas so that $\dot{E} = 3Nk\dot{T} + 3\dot{N}kT$. Then, the contribution to $\dot{T}$ from evaporation is proportional to $\dot{N}(U + \alpha kT - 3kT)$. Hence, the cooling rate is proportional to the difference between the average energy carried away per particle ($\simeq U + \alpha kT$) and the average thermal energy $3kT$, as it should be.

Solving Eq. (2) with a fixed value of $U/kT = \eta$, the number of trapped atoms is found to vary with trap depth as

$$\frac{N}{N_i} = \left(\frac{U}{U_i}\right)^{3/[2(\eta' - 3)]}, \tag{3}$$

where i denotes the initial condition at $t = 0$, $N = N(t)$, and $U = U(t)$. Here, $\eta' = \eta + \alpha = \eta + (\eta - 5)/(\eta - 4)$. The corresponding phase-space density in the classical regime is $\rho = N(h\nu)^3/(kT)^3$, where $\nu = \nu(t) \propto \sqrt{U}$ is the geometric mean of the trap oscillation frequencies. Using Eq. (3), it is easy to show that $\rho = \rho(t)$ scales with trap depth and number as

$$\frac{\rho}{\rho_i} = \left(\frac{U_i}{U}\right)^{3(\eta' - 4)/[2(\eta' - 3)]} = \left(\frac{N_i}{N}\right)^{\eta' - 4}. \tag{4}$$

Equation (4) shows that for $\eta = 10$, $\rho/\rho_i = (U_i/U)^{1.3}$. For an initial phase-space density of $\rho_i = 3 \times 10^{-3}$, lowering the well depth by a factor of 84 yields $\rho = 1$. For an energy-independent scattering cross section, the elastic collision rate $\gamma = \gamma(t) \propto N\nu^3/(kT)$ scales with trap depth as

$$\frac{\gamma}{\gamma_i} = \left(\frac{U}{U_i}\right)^{\eta'/[2(\eta' - 3)]}, \tag{5}$$

and is reduced by a factor of 21 for a factor of 84 reduction in well depth when $\eta = 10$.

An important feature of Eq. (4) is that the increase in phase-space density with decreasing number is identical to that obtained using a radio-frequency-knife method with a trap depth to thermal energy ratio of η. This is a consequence of the adiabatic energy loss, which ensures that the phase-space density does not change as the trap depth is lowered when $\dot{N} = 0$. Hence, the phase-space change arises only from evaporation as in the radio-frequency-knife method. For an optical trap with $\eta = 10$, $\rho/\rho_i = (N_i/N)^{6.8}$, and a modest decrease in number leads to a great increase in phase-space density. Unlike evaporation from a fixed well, however, the collision rate for an energy-independent elastic cross section decreases as $(U/U_i)^{0.69}$ for $\eta = 10$, and runaway evaporation is not achieved [17]. Nevertheless, for atoms such as ^{6}Li, where the scattering length is anomalously large, evaporation is still rapid and the background collision induced loss can be minimized despite the reduced collision rate.

The scaling laws are derived neglecting background gas collisions. To include background gas collisions, a loss rate term $-\Gamma_{bg}E$ is included in Eq. (2) and $\dot{N}$ is replaced by $\dot{N}_{evap}$, where the evaporation rate $\dot{N}_{evap} = \dot{N} + \Gamma_{bg}N$. Then, one can show that the scaling laws for the number, collision rate, and phase-space density versus trap depth are reduced by a factor $\exp(-\Gamma_{bg}t)$, where t is the time over which the trap depth is lowered. Different exponential factors can be derived for the scaling laws versus number. Equation (2) is also readily modified to include effects of residual heating.

Although the derivation of the scaling laws does not explicitly include the time dependence of the trap depth, maintaining a constant value of η specifies the time dependence $U(t)$, which follows from the evaporation rate. To lowest order in $\exp(-\eta)$, and neglecting background gas collisions, we obtain from the s-wave Boltzmann equation [14],

$$\dot{N} = -2(\eta - 4)\exp(-\eta)\gamma N. \tag{6}$$

Differentiating Eq. (3) and writing γ/γ_i in terms of U/U_i, we obtain

$$\frac{U(t)}{U_i} = \left(1 + \frac{t}{\tau}\right)^{-2(\eta' - 3)/\eta'}, \tag{7}$$

where the time constant τ is given by

$$\frac{1}{\tau} = \frac{2}{3}\eta'(\eta - 4)\exp(-\eta)\gamma_i. \tag{8}$$

Including background gas collisions changes $t \rightarrow [1 - \exp(-\Gamma_{bg}t)]/\Gamma_{bg}$ in Eq. (7). Equation (8) shows that the lowering rate scales with the initial collision rate γ_i. According to Eq. (7), the rate of decrease of the well depth decreases with time as the collision rate, and hence, the evaporation rate declines. The initial elastic collision rate for a single state Bose gas in a harmonic potential is $\gamma_i(\mathrm{sec}^{-1}) = 4\pi N_i M \sigma \nu_i^3/(kT_i)$, where N_i is the total number of atoms initially in the trap, T_i the initial temperature, $\sigma = 8\pi a^2$, and ν_i is the initial mean trap oscillation frequency in Hz. For a two-state 50-50 mixture of fermions with the same mass, scattering length, total number, and trap frequencies as in the Bose case, the rate is reduced by a net factor of 4.

The scaling law predictions are valid for both bosons and fermions in the classical regime, where the effects of quantum statistics can be neglected. We have compared the scaling law predictions to a detailed Boltzmann equation model for evaporation of a two-state mixture of fermionic ^{6}Li in a single gaussian beam optical trap. Assuming sufficient ergodicity, the evolution of a low-temperature trapped gas in a time-dependent potential is described by the s-wave Boltzmann equation [13,14], which we write in the form [18],

$$\frac{\partial f(\epsilon,t)}{\partial t} + \langle \dot{U}(\epsilon,t) \rangle \frac{\partial f(\epsilon,t)}{\partial \epsilon} = \left(\frac{df}{dt}\right)_{coll}. \tag{9}$$

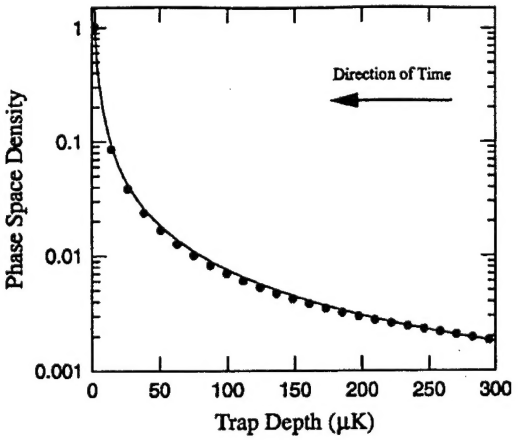

FIG. 1. Phase-space density (each state) vs trap depth. S-wave Boltzmann equation model (dots); scaling law predictions (solid line). The time varies from 0 to 36 sec.

The left-hand side of Eq. (9) describes the adiabatic evolution of the gas in the time-dependent potential. Physically, in a time Δt, the occupation number $f(\epsilon,t)$ changes adiabatically according to $f(\epsilon,t+\Delta t)=f(\epsilon-\Delta t(\partial H/\partial t),t)$. Hamilton's equations require $\langle \partial H/\partial t\rangle=\langle \dot{U}(\epsilon,t)\rangle$, where the angular brackets denote the ergodic average of the time rate of change of the potential [18]. The right-hand side of Eq. (9) is a Boltzmann collision integral, which redistributes the level occupation numbers $f(\epsilon,t)$ including Fermi statistics [18].

A comparison of the results of the scaling laws and the Boltzmann equation predictions for a two-state mixture of ^{6}Li fermions is shown in Figs. 1 and 2. The scattering length is taken to be $a=-300\,a_0$, which can be obtained by applying a magnetic field of 300 G. The trap parameters are as follows: $N_i=4\times10^5$ (total), $\nu_i=1300$ Hz, $T_i=30$ μK, $U_i=300$ μK, i.e., $\eta=10$ and $\Gamma_{bg}=0.003$ s^{-1}. The well depth is lowered according to Eq. (7) with $\eta=10$ using a time constant τ of 1.2 seconds, as predicted by Eq. (8). With these parameters, the Boltzmann model yields U/kT between 10

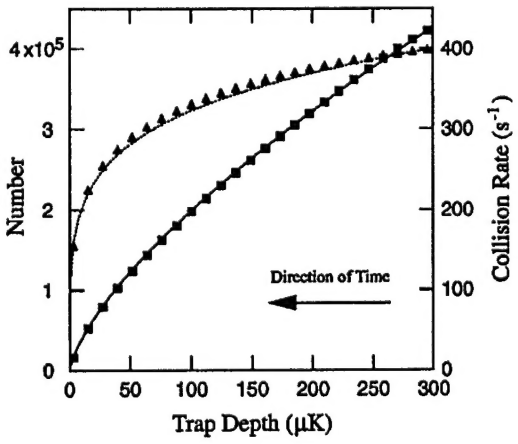

FIG. 2. Number and collision rate vs trap depth. S-wave Boltzmann equation model: Number (triangles); collision rate (squares); scaling law predictions (lines). The time varies from 0 to 36 sec.

and 9.6. Using $\eta=10$ in the scaling laws, we obtain nearly perfect fits to the Boltzmann model up to a phase-space density of 1, where the effects of Fermi statistics become important. For exponential lowering of the trap depth, where η is only approximately constant, the scaling law fits are in reasonable agreement with the Boltzmann model, although the fits are not quite as good as for constant η.

For completeness, we describe briefly why Fermi statistics does not severely suppress the efficiency of evaporative cooling. When $T\ll T_F$ the collision rate within the trap is reduced to $\Gamma\propto\gamma_{cl}(T/T_F)^2\ll\gamma_{cl}$, where γ_{cl} is the classical collision rate evaluated at the Fermi surface, T is the temperature, and T_F is the Fermi temperature [19]. The factor $(T/T_F)^2$ is a consequence of Pauli blocking, which forbids collisions into occupied energy states, as observed recently [20]. However, in evaporation, one of the final states is essentially unoccupied, since it is outside the trap. Hence, the evaporation rate is suppressed by only T/T_F, i.e.,

$$\Gamma_{evap}\propto\gamma_{cl}\frac{T}{T_F}\exp\left(-\frac{U-kT_F}{kT}\right).$$

The exponential factor describes the high-energy tail of the Fermi distribution, which is responsible for evaporation when the trap depth $U\gg kT$. This is essentially the same factor that appears in the evaporation of a classical gas. Since the heat capacity also scales as T/T_F [21], the efficiency of evaporative cooling in lowering the temperature is not seriously compromised in a two-component Fermi gas, although the sensitivity to residual heating is increased. Further, the collision rate within the trap is always fast compared to the evaporation rate when $U-kT_F\gg kT$, since $T/T_F\gg\exp[-(U-kT_F)/kT]$ so that rethermalization is faster than evaporation. This picture explains why Pauli blocking does not appear to strongly affect the rate of decrease of T/T_F in a recent theoretical model of evaporation for a two-component Fermi gas [22].

It is interesting to compare the scaling law predictions with the experimental BEC results obtained by Barrett *et al.* [11]. We take N_i to be the stagnation value after 1 second [11], about 1/3 of the maximum number loaded. In the actual experiments, the gas is not given time to stagnate before the trap lowering begins, but one expects that most atoms are lost in a small fraction of a second before the well depth changes appreciably, since the evaporation slows exponentially as the temperature drops to less than 1/10 of the well depth in the first second. For the final conditions, we use the data for a laser power of $P=350$ mW, near the transition between the classical and degenerate regimes, where the scaling law is approximately valid. We use the trap lifetime of 6 sec and a lowering time of 2.5 sec to obtain a background loss factor of $\exp(-\Gamma_{bg}t)=\exp(-2.5/6)=0.66$. The well is assumed to be lowered by a factor $U_f/U_i=(\nu_f/\nu_i)^2=1/84$, based on the measured trap oscillation frequencies. We take $\eta=U/kT=10$ and give results for the case where all atoms are in a single hyperfine state. Table I shows that the predictions are in good agreement with the experiments for these reasonable assumptions about the trap parameters.

TABLE I. Comparison of scaling law predictions with the BEC experiment of Ref. [11].

Initial conditions	Final conditions	Predictions
$\nu_i = 1500$ Hz	$\nu_f = 164$ Hz	
$N_i = 6.7\times 10^5$	$N_f = 1.8\times 10^5$	$N_f = 1.9\times 10^5$
$T_i = 38$ μK	$T_f = 375$ nK	$T_f = 450$ nK
$\gamma_i = 12\times 10^3$ sec^{-1}	$\gamma_f = 300$ sec^{-1}	$\gamma_f = 372$ sec^{-1}
$\rho_i = 1/200$	$\rho_f = 1.4$	$\rho_f = 1.1$

In conclusion, we have derived simple scaling laws for the number, collision rate, and phase-space density as a function of trap depth for atoms in a time-dependent, adiabatically lowered optical trap operating near stagnation. The inclusion of the time-dependent potential in the Boltzmann evolution equation and in the scaling law model is essential, as it accounts for the adiabatic energy loss in the trap, which is needed to preserve the phase-space density in the absence of evaporation. Our results show that the phase-space density in optical traps increases rapidly as the trap depth is lowered, when the ratio of trap depth to temperature is large. The reduction of the elastic collision rate with well depth is mitigated by the large initial spatial [11,23] and phase-space densities obtainable with optical traps, as well as the large scattering lengths obtainable in some systems. Hence, evaporation in optical traps appears quite promising as a means to achieve degeneracy in a variety of atomic and molecular systems. Finally, we have presented a physical picture to explain why Pauli blocking does not strongly inhibit cooling by evaporation in fermionic mixtures.

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